FAULT DIAGNOSIS OF A HVDC SYSTEM USING PATTERN MATCHING

by

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INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

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CERTIFICATE

This is to certify that this work entitled " FAULT DIAGNOSIS OF A HVDC SYSTEM USING PATTERN MATCHING " by Sushil Kumar Srivastava has been carried out under our supervision and that this work has not been submitted elsewhere for the award of a degree.

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ABSTRACT

This thesis deals with the fault diagnosis of the hvdc system using pattern matching. The disturbances considered are ac voltage dips on rectifier as well as on inverter side and dc line faults occurring at different locations on the dc line. The system response to various disturbances has been obtained from the dynamic digital simulation of the hvdc system. The time domain discriminants have been calculated from these responses. The rectifier end direct current has been used to calculate these discriminants. Further, the log - transformed value of direct current has also been used to calculate the discriminants in order to improve the resolution in the values of the discriminants obtained for various disturbances. It has been found that the individual discriminants can not differentiate all of the disturbances. A combination of these discriminants have been used through a pattern matching technique to detect the various disturbances. The pattern matching technique, which has been used,is based on the concept of distance measure.

CHAPTER 1

INTRODUCTION

The high voltage direct current (hvdc) transmission system has now emerged as a viable alternative to the high voltage alternating current transmission system for bulk power and long distance transmission and interconnection of ac systems. With the evergrowing use of the hvdc transmission system this has become the most promising area for the research oriented studies. This thesis is a step in this direction.

One of the major advantages of the hvdc transmission is its fast controllability. The behaviour of an hvdc system following a disturbance is predominantly affected by controller parameters. It has been proposed that the adaptive control for hvdc system shows better result than fixed parameter controllers [1]. However, the convergence time required for the adaptive control algorithm may be significant [2]. Further, it has been suggested that the look up table concept can overcome the problem of slow convergence associated with the adaptive control algorithm. One of the essential steps in the application of look up table concept is fast state identification for making decision about the choice of controller parameters. In the literatures [3-5], the system state identification using pattern matching techniques have been suggested. It has also been reported that the pattern matching technique is computationally time intensive. In this thesis an attempt has been made to explore the possibilities of applying the pattern matching technique for fault diagnosis of a hvdc system. The next section deals with the basics of the pattern matching which has been

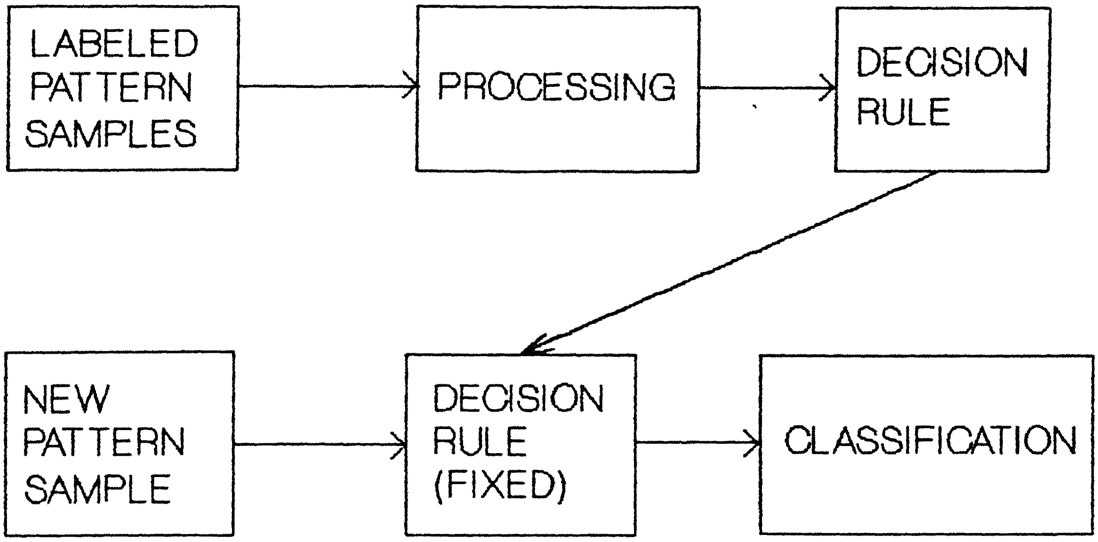


Fig. (1.1a): Learning before recognition

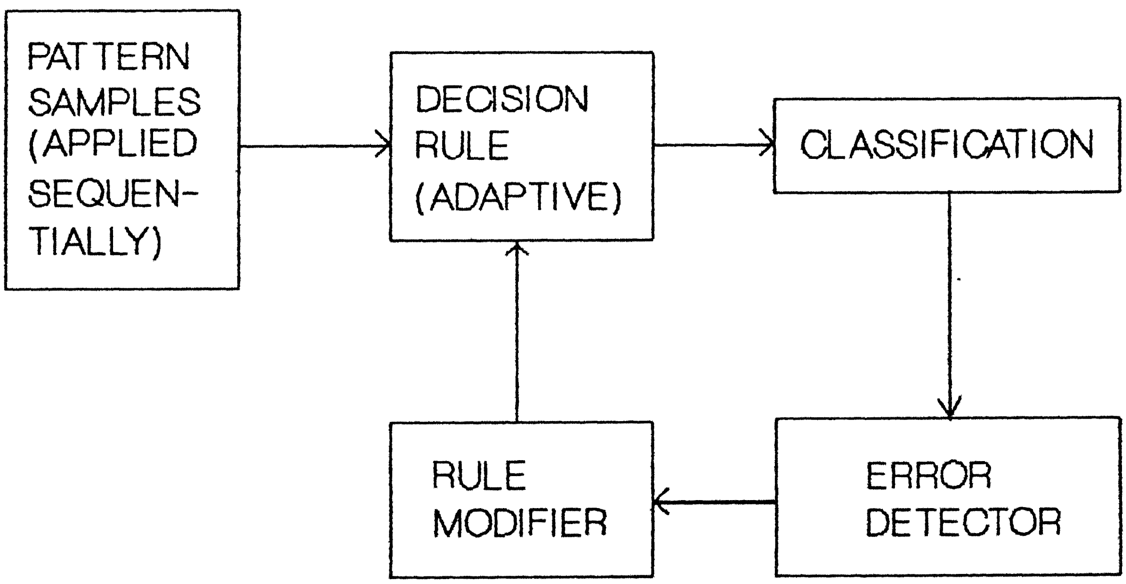


Fig. (1.1b): Learning and Recognition concurrently

(Ref:"Computer oriented approches to pattern recognition"by W.S.Meisel)

used subsequently for the fault diagnosis of a hvdc system.

1.1 PATTERN MATCHING

Pattern matching begins with the class definition and labeled samples of those classes in some workable representation. The problem is solved when a decision rule is derived, which assigns a unique label to new pattern. There are two aspects of pattern matching namely developing a decision rule and using it [6].

The two stages of pattern matching, deriving a decision rule and using it , can be performed concurrently and sequentially. In Figure 1.1a the sequential procedure has been presented. In this method all the labeled pattern samples are collected and best decision rule based on those samples is derived. That decision rule is used without change to classify the unlabeled samples. Figure 1.1b shows the concurrent procedure. In this case the decision rule is modified as it is used. Here a sample pattern is presented and classified , an error detector indicates whether the classification is correct or not and the decision rule is left unchanged or modified as appropriate. In this thesis the sequential procedure of pattern matching is used.

The process, necessary in deriving the decision rule, is indicated diagramatically in Figure 1.2. The system from which the given pattern arises is characterised completely by its physical embodiment. Raw data describing the system is referred as the measurement space. The pattern space may be identical with the measurement space or several stages of intermediate

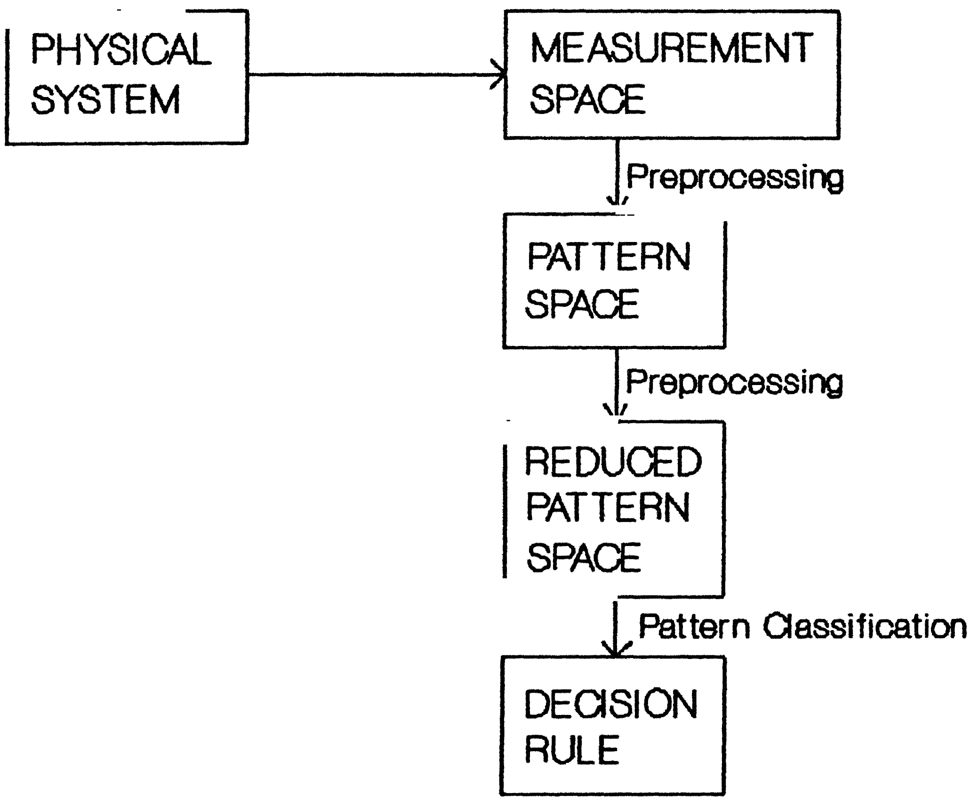


Fig. 1.2: Stages in the Derivation of decision Rule

processing may be necessary. Feature selection (or preprocessing) is a process by which a sample pattern in the measurement space is described by a finite and usually smaller set of numbers called features.

1.2 OBJECTIVE OF THE THESIS

The need of a fast state identification technique has been established in the foregoing discussion. The main objective of the thesis is to develop a fault diagnosis technique using pattern matching to identify the various disturbances occurring in the two terminal high voltage direct current transmission system.

1.3 ORGANISATION OF THE THESIS

To meet the objective of fault diagnosis of the hvdc system the dynamic digital simulation of an hvdc system has been carried out for obtaining the system response to various disturbances. The digital computer representation of the hvdc system has been discussed in chapter 2. Both the conventional and unconventional control strategies of the hvdc system have been discussed. The recovery from the various disturbances has been validated with unconventional control at the inverter terminal.

Chapter 3 deals with the time domain technique for the identification of disturbances. The various time domain discriminants have been discussed and their values have been obtained from the system response. The success of individual discriminants for the identification of disturbances has been examined.

The pattern matching technique used for the identification of various disturbances has been discussed and

utilized in chapter 4. Software for the fault diagnosis based on pattern matching technique has been developed. The identification of the disturbances has been validated. Another system operating condition (with unconventional control at inverter) has been considered to examine the effect of operating condition on the identification process.

The conclusions and future scope of this work have been presented in chapter 5.

CHAPTER 2

HVDC SYSTEM SIMULATION

2.1 INTRODUCTION

One of the major steps in the state identification procedure is to establish the knowledge about the system behaviour following a disturbance. With this objective the dynamic digital simulation of the hvdc system has been attempted. This chapter briefly describes the representation of the various subsystems(the ac system feeding the converters,converters and the associated controls and dc transmission network) for the purpose of simulation. In addition to the conventional control strategy of constant current and extinction angle controls,the unconventional control(Constant Reactive Current control) for inverter has also been considered. Based on these control strategies the transient behaviour of the two terminal hvdc system has been studied to derive the appropriate knowledge for state identification.

2.2 HVDC SYSTEM REPRESENTATION

The approach employed for the representation of the hvdc system is to model each component or subsystem separately in a modular fashion. The various subsystem models are then interconnected using appropriate interfacing variables. The representation of various components of hvdc system is briefly described below.

2.2.1 Converter Representation

The converters which link two ac systems are represented as a variable voltage source behind a variable

impedance. The converter equivalent circuit is shown in Figure 2.1. The voltage source (e_{eq}) in equivalent circuit is a function of ac bus voltage and hence has to be calculated at each time instant. The equivalent circuit parameters R_{eq} and L_{eq} are dependent on the converter conduction pattern and are recalculated every time as the conduction pattern is changed. The source V_g has been included to represent the effect of the dc system. Both the ac and dc voltage sources are the outputs of the ac and dc network models [12]. R_d and L_d denote the resistance and inductance of the smoothing reactor.

2.2.2 Control Representation

(a) Conventional Control

The hvdc converters are generally equipped with constant current and constant extinction angle controls. These are called as conventional controls. The controls of converters considered here are based on the digital technique proposed by Freris et al. [7]. The firing scheme is equidistant pulse control with pulse frequency control. The Inter Firing Period (IFP), which is the interval between two successive firing instant, is calculated as

$$IFP = 60^0 + Q_i$$

where Q_i is the firing correction obtained from constant current or constant extinction angle control. Under steady state Q_i=0 and firing takes place at 60^0 interval. In case of constant current control, the firing correction is obtained as

$$Q_i = KV_c$$

where K is the gain and V_c is the control signal. The block diagram for the calculation of IFP and firing

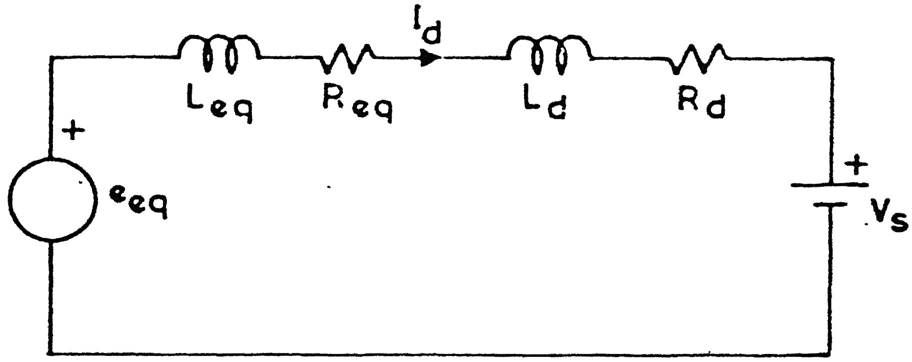


FIG.2.1. EQUIVALENT CIRCUIT OF 6 PULSE CONVERTER

correction is shown in Figure 2.2. The control signal V_c may be a linear function of current error as

$$V_c = K_1(I_d - I_{d\ ref})$$

Arrillaga [8], however, has suggested that the inclusion of a derivative term in the calculation of control voltage improves the dynamic behaviour of the system. Then control signal becomes

$$V_c = K_1(I_d - I_{d\ ref}) + K_2(dI_d/dt)$$

The control signal V_c is sampled and used for the calculation of firing correction.

In case of constant extinction angle control the controller action takes place through two completely independent loops. These are inverter safety control and inverter optimum control. The extinction angle (Γ) is the current zero instant of a particular valve and the instant at which the voltage across it becomes positive again. The controller , by changing the firing instant , attempts to keep this angle at its specified minimum value. The change in the firing instant is accomplished according to the difference between the measured Γ and Γ reference.

The inverter safety control acts when the measured Γ is less than the Γ reference and it can only reduce the firing angle. The firing correction is obtained as

$$Q_i = K_3(\Gamma - \Gamma_{ref})$$

The inverter optimum control tries to bring the system back to its optimum operating condition when the inverter safety is guaranteed. To obtain this, a record is kept of all the extinction angle measured in a cycle and if minimum of all these

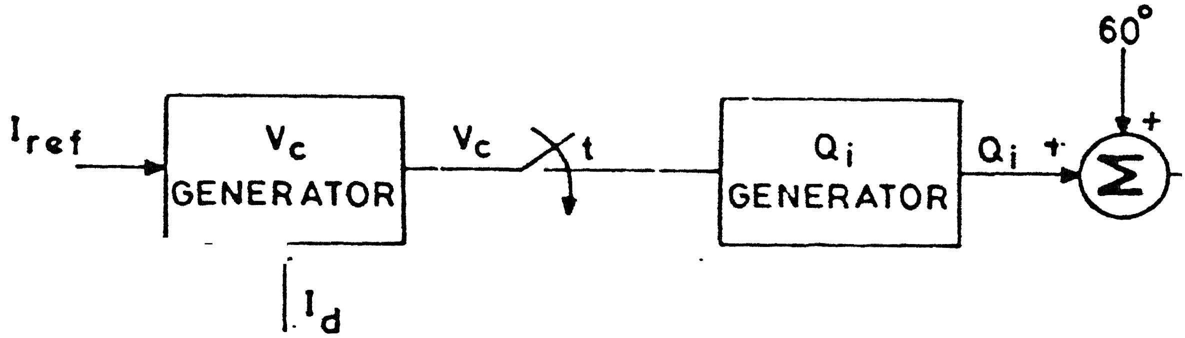
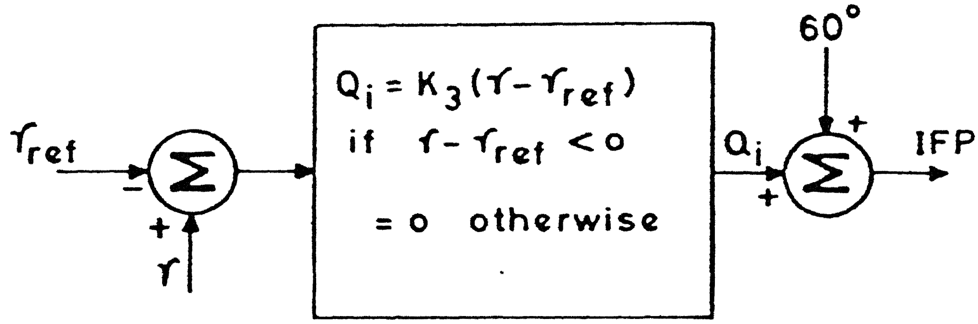
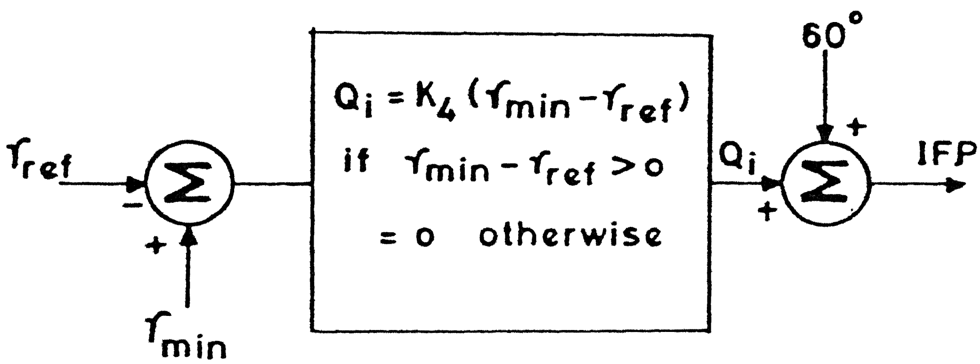


FIG. 2.2 CONSTANT CURRENT CONTROL



INVERTER SAFETY CONTROL



INVERTER OPTIMUM CONTROL

FIG. 2.3. CONSTANT EXTINCTION ANGLE CONTROL

extinction angles is greater than Γ reference the firing angle is increased. Thus the inverter optimum control operates only once in a cycle and the firing correction is obtained as

$$\Omega_1 = K_4(\Gamma_{min} - \Gamma_{ref})$$

The block diagram for the calculation of firing correction and IFP for constant extinction angle control is shown in Figure 2.3.

(b) Unconventional Control

To investigate the influence of other control scheme on the fault diagnosis , an unconventional control has also been considered for the inverter. The various unconventional controls are the power factor control, the constant reactive power control, the constant reactive current control etc. The unconventional control considered, is based on constant reactive current control suggested by Szechtman et al. [9].

Szechtman et al. [9] have shown that the constant reactive current control has a superior general behaviour compared to the conventional control. The inverter when in voltage control , which is the normal condition , exhibits a negative impedance characteristic that may affect the over all system stability. Weaker the ac system more pronounced is the negative impedance effect and therefore, the voltage instability problem is aggravated. The voltage instability problem could be minimized using compensation techniques. Thus the principle of minimizing reactive power consumption by operating inverter at minimum extinction angle is partially ineffective as it requires more voltage support.

To circumvent the above problem , an alternate

technique based on the control of reactive current at the inverter has been suggested [9]. The firing angle of the inverter is regulated in a manner that the reactive current absorbed by the inverter remains constant. The calculation of firing correction and IFP is same as in case of constant current control. The control signal V_c is generated as a function of converter reactive current and reference reactive current. A derivative term has been included to improve the dynamic behaviour of the system [9]. The control signal V_c is obtained as

$$V_c = K_1(I_q - I_{q\ ref}) + K_2(dI_q/dt)$$

The values of gain K_1 and K_2 have been chosen judiciously. The control signal V_c is sampled and used to calculate the firing correction based on Pulse Frequency Control as

$$Q_1 = KV_c$$

The firing correction thus obtained is used to calculate the IFP which decides the next firing instant. Under steady state the firing correction (Q_1) is zero and firing takes place at 60^0 interval.

2.2.3 AC AND DC NETWORK REPRESENTATION

The ac system is represented by an ideal voltage source behind a T - equivalent circuit as described in [10]. A three phase schematic representation of the ac system and harmonic filters associated with a particular terminal is shown in Figure 2.4.

The inductance (L_s) and resistance (R_s) are determined at fundamental frequency from the knowledge of short

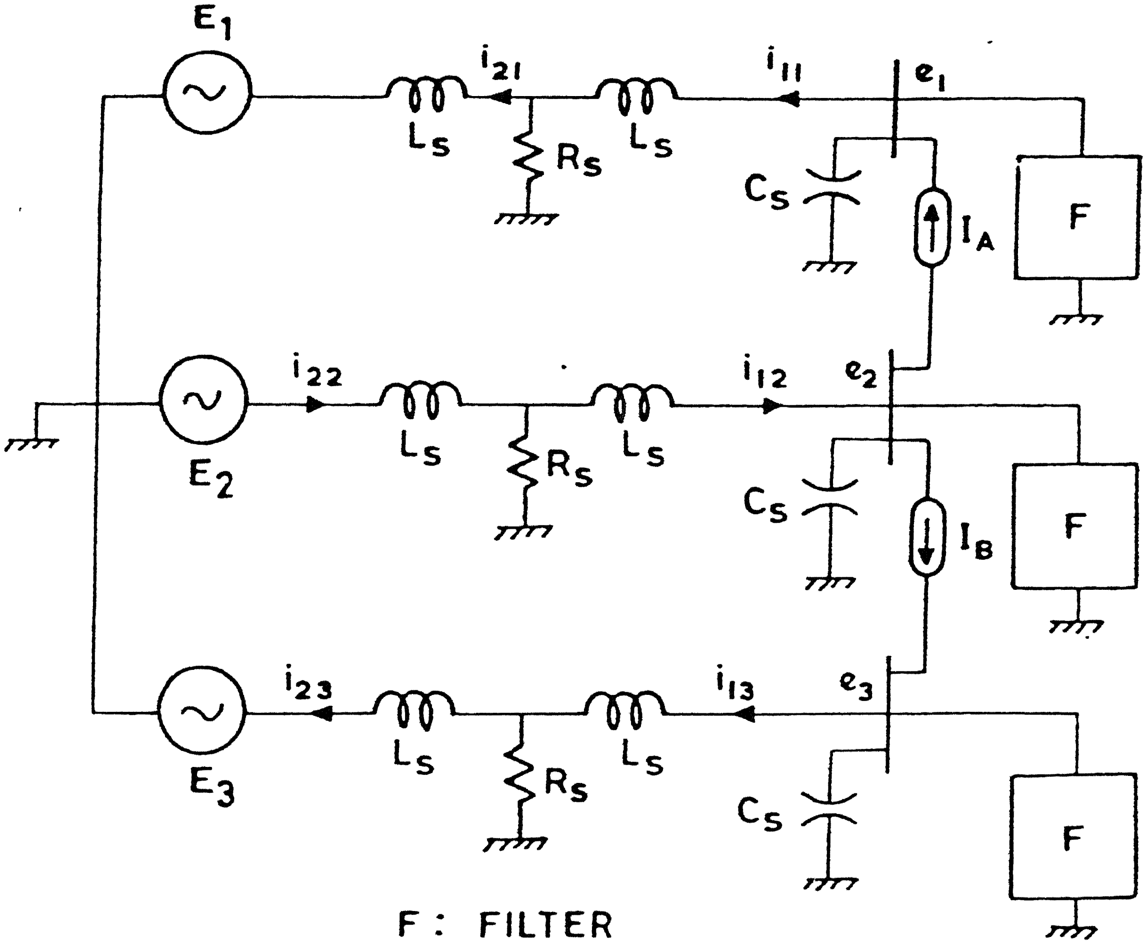


FIG. 2.4. AC SYSTEM REPRESENTATION

circuit ratio and impedance angle at the converter terminal. The effective short circuit ratio gets modified in the presence of harmonic filters and/or shunt capacitors. The calculations of effective short circuit ratio and other ac system parameters have been reported in reference [11]. The shunt capacitor (C_s) has been chosen based on reactive power requirement of the converters. The effect of converters on the ac system are represented by current sources I_A and I_B. The tuned harmonic filters for 5^{th},7^{th},11^{th} and, 13^{th} order harmonic with a second order high pass filter have been represented at the converter bus.

The dc network comprises of dc filters , smoothing reactors and transmission lines. The transmission line is modelled as a Pi - equivalent circuit with the shunt arms consisting of capacitors, and series arm a combination of resistance and inductance. A more practical representation of transmission line is a number of Pi - section. This is done by dividing the transmission line into a number of sections, representing each section by its own Pi - network and connecting all such networks in series. In the dc system representation converters are represented as current source as shown in Figure 2.5. The dc filters , used for filtering any harmonic present in the direct current, are also represented in dc system model.

2.3 COMPUTER PROGRAM

A computer program, based on the representation discussed in the preceding sections, has been developed and reported in reference [12]. This incorporates both 6 and 12 pulse converter representations along with analog firing control scheme

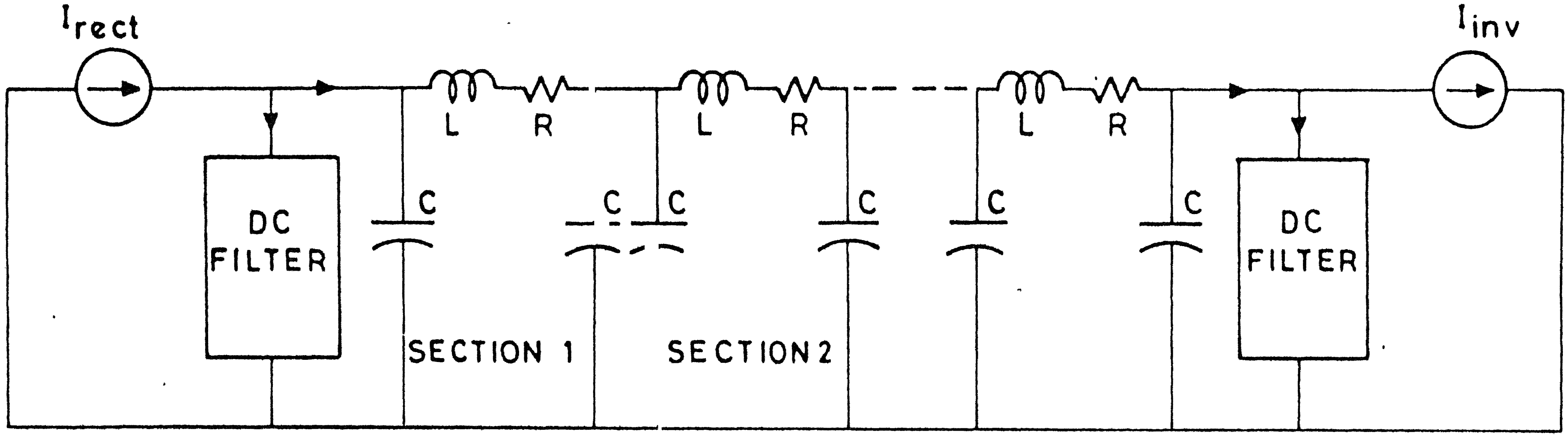


FIG. 2.5. DC LINE AND FILTER REPRESENTATION

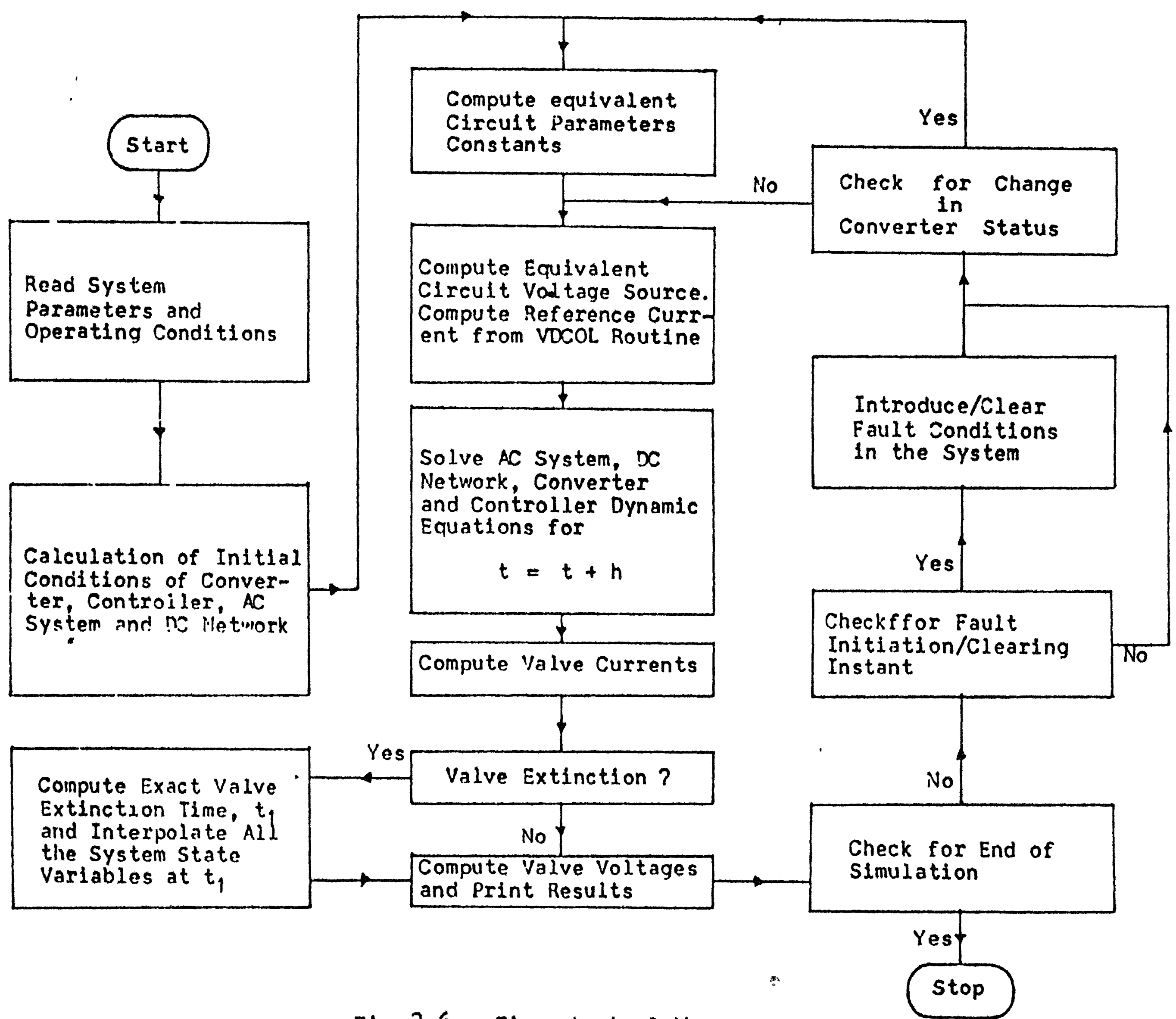


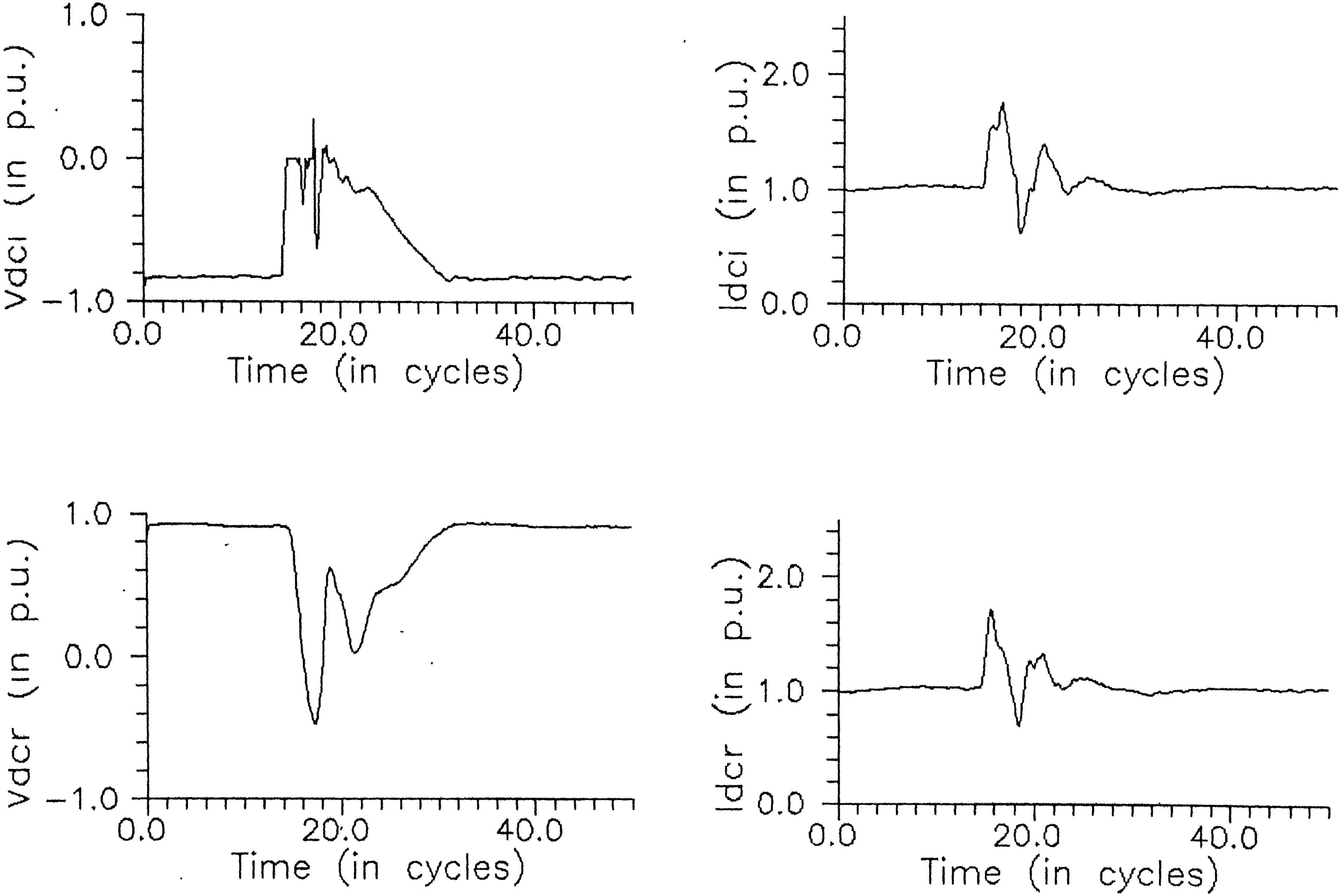
Fig. 2.6. Flow chart of the program.

based on IPC and EPC. The program is extremely modular and therefore permits the implementation of different control schemes and other advanced features necessary to simulate the practical system. The program was augmented and reported in the reference [11], to incorporate the digital firing control scheme as given by Freris et al.[7]. The program is augmented to incorporate unconventional control (Constant Reactive Current Control) at the inverter terminal . The fault diagnosis subroutine has been developed, based on pattern matching technique, for the identification of various types of faults. The basic flow chart of augmented program is given in Figure 2.6.

The simulation can start either assuming the system under steady state operating condition or with zero initial condition. In the former case the initial conditions for various state variables have to be supplied. The calculation of initial conditions for various state variables have been reported in reference [11].

2.4 CASE STUDY

The augmented computer program is used to carry out various test simulations. The dynamic behaviour for various disturbances has been studied under unconventional control at the inverter terminal. The various types of disturbances given in Table 2.1 have been simulated. The recovery from these disturbances with constant reactive current control at inverter has been tested. The system response, for line to ground fault at inverter with conventional and unconventional, is shown in Figures 2.7 and 2.8. The recovery time with conventional and


Vdci (in p.u.)
1.0
0.0
−1.0
0.0
20.0
40.0
Time (in cycles)
Idci (in p.u.)
2.0
1.0
0.0
0.0
20.0
40.0
Time (in cycles)
Vdcr (in p.u.)
1.0
0.0
−1.0
0.0
20.0
40.0
Time (in cycles)
Idcr (in p.u.)
2.0
1.0
0.0
0.0
20.0
40.0
Time (in cycles)

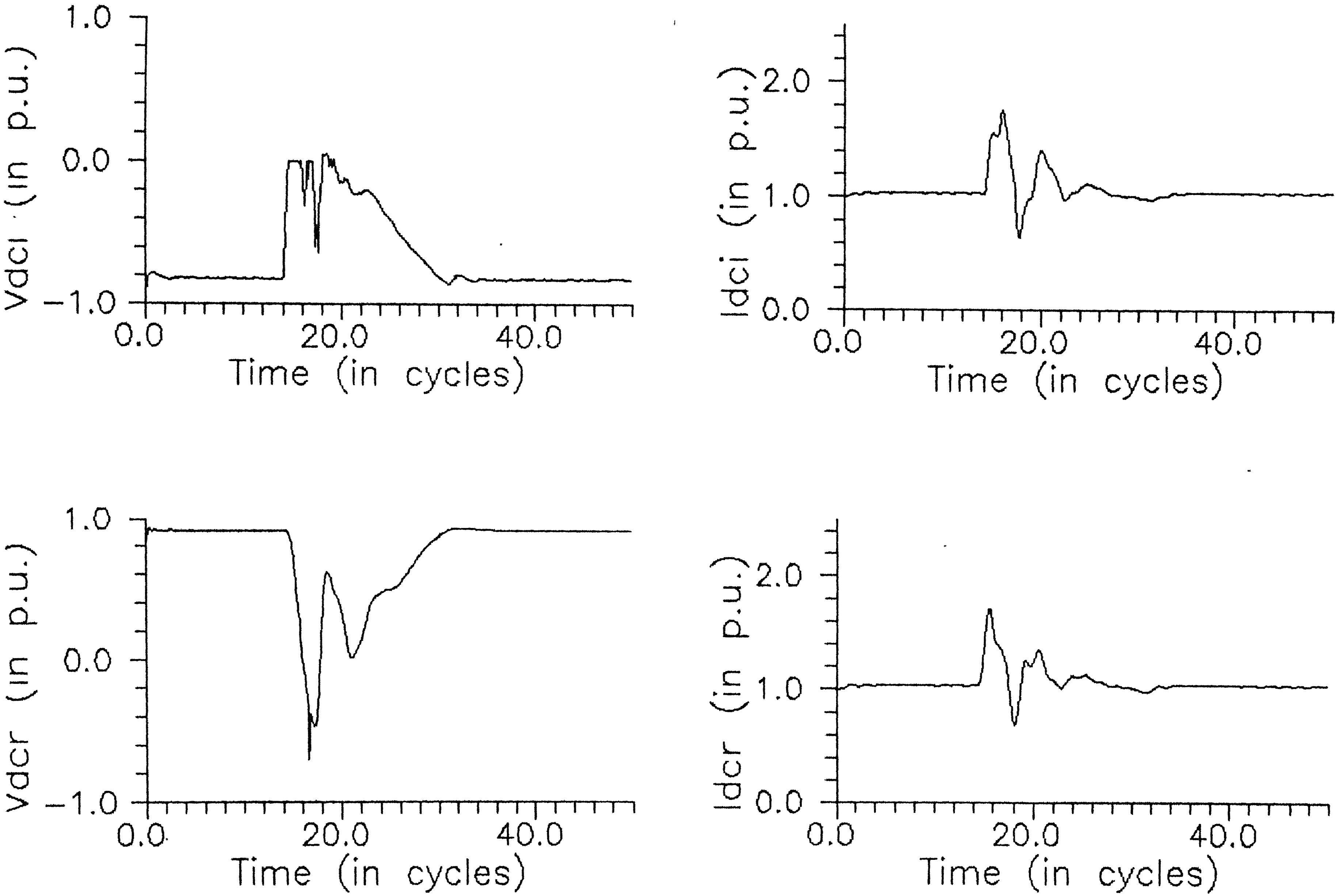


Fig −(2.8):L−G fault at inverter bus(Constant reactive

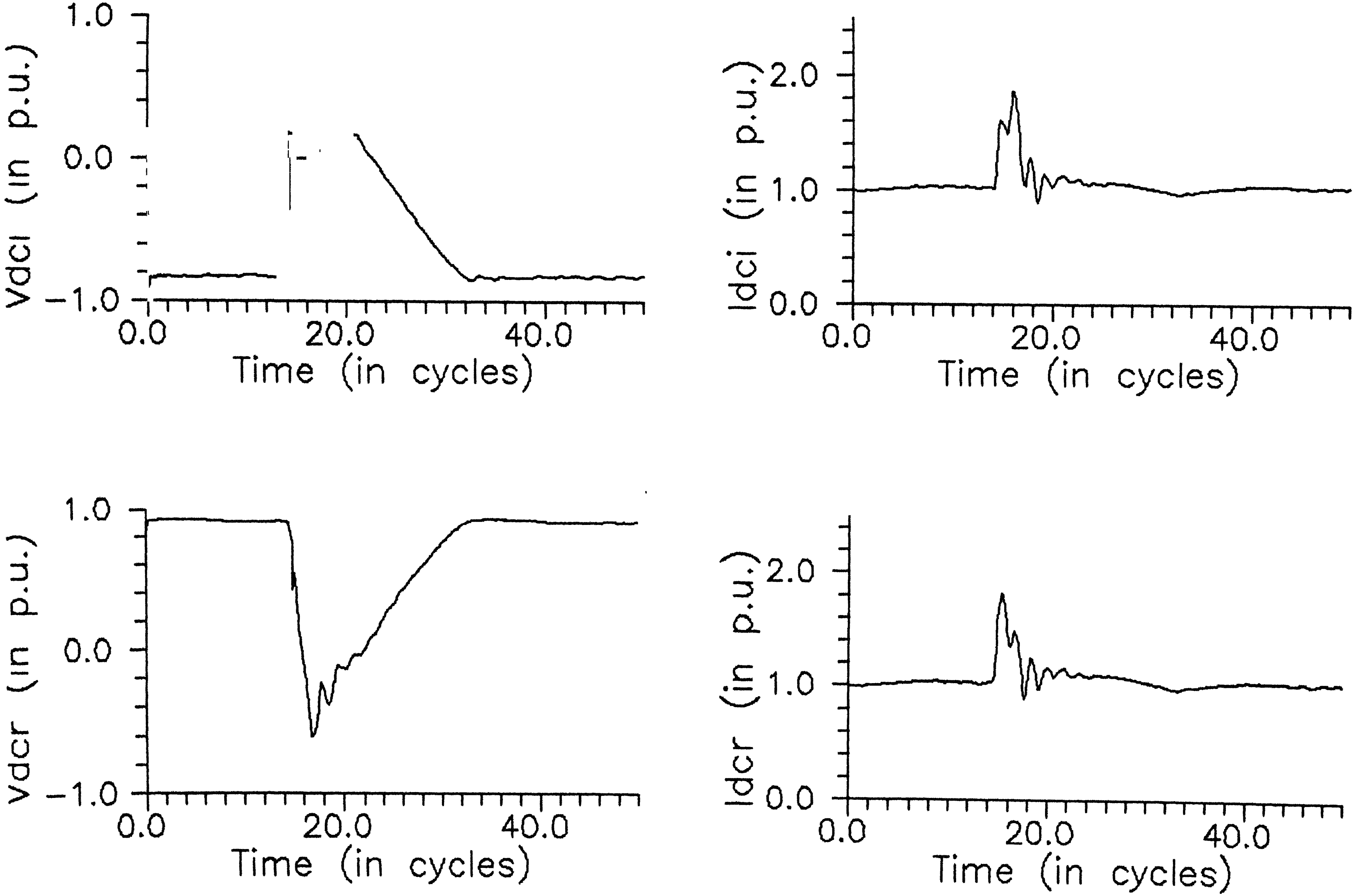


Fig. 2.9 : Three Phase Fault at Inverter

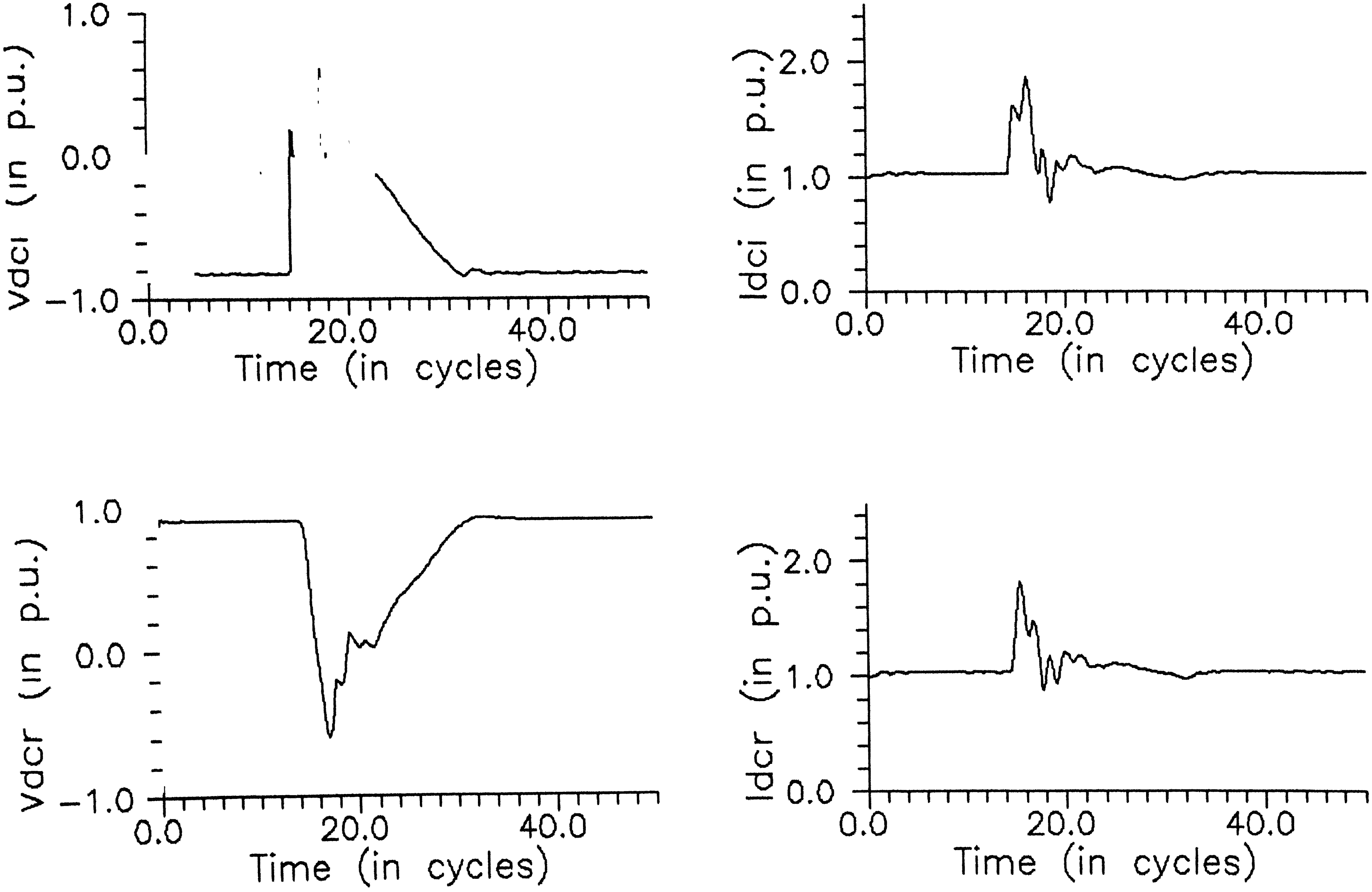


Fig. 2.10 : Three Phase Fault at Inverter

unconventional control is same and it is approximately 280 ms. The recovery from three phase fault at inverter is shown in Figures 2.9 and 2.10 with conventional and unconventional controls respectively.

2.5 DISCUSSION

The digital computer representation of the hvdc system has been discussed in this chapter. Both the conventional and unconventional controls for the inverter terminal have been discussed. The digital computer program is augmented to incorporate an unconventional control (Constant Reactive Current Control) at the inverter terminal. The recovery from the various disturbances has been studied. The system response to various disturbances, obtained from the dynamic digital simulation of the hvdc system with conventional and un conventional controls, has been used to obtain the time domain discriminants in the following chapters.

CHAPTER 3

TIME DOMAIN TECHNIQUE

3.1 INTRODUCTION

In this chapter various types of time domain discriminants have been discussed. These discriminants are used to identify various types of disturbances. The discriminants are calculated from the system response to various disturbances obtained from dynamic digital simulation of the hvdc system. The rectifier side direct current is used as a signal for the calculation of these discriminants. Another signal which is the log - transformed value of direct current has also been considered. The disturbances considered are the ac voltage dips and dc line faults occurring at different locations on the ac and dc sides.

3.2 TIME DOMAIN DISCRIMINANTS

The following time domain discriminants have been considered for the identification of various disturbances [13].

(1) Mean

The mean value of a signal is defined as

$$\text{Mean } (\mu) = \frac{\sum_{i=1}^{N} X_i}{N}$$

where, X_i = The value of signal at i^{th} instant

N = The number of samples

(2) Variance / Standard Deviation

The second moment about the mean is called the variance of the signal. Mathematically the variance of a signal is defined as

$$\text{Variance } (\sigma) = \frac{\sum_{i=1}^{N} (X_i - \mu)^2}{N}$$

The square root of the variance is called the standard deviation of signal distribution.

(3) Skewness

Skewness, the third moment about the mean, gives a measure of skewness or asymmetry of the distribution. Mathematically skewness is defined as

$$\text{Skewness (S)} = \frac{1}{N} \frac{\sum_{i=1}^{N} (X_i - \mu)^3}{\sigma^{3/2}}$$

(4) Kurtosis

Kurtosis, the fourth moment about the mean, gives the measure sharpness. Mathematically Kurtosis is defined as

$$\text{Kurtosis (K)} = \frac{1}{N} \frac{\sum_{i=1}^{N} (X_i - \mu)^4}{\sigma^2}$$

(5) Area/Integral

Area under the distribution can be calculated by using Simpson's formula for integration. The Simpson's formula for integration can be approximated as

$$\int_{X_0}^{X_2} Y(X)\, dX = \frac{h}{3} (Y_0 + 4Y_1 + Y_2)$$

Where,

$$Y_0 = Y(X_0)$$

$$Y_1 = Y(X_0 + h)$$

$$Y_2 = Y(X_0 + 2h)$$

h = Integration step length

$Y(X)$ = Distribution function

This gives the area of the strip lying between X_0, X_2 and Y_0, Y_2. Area under the distribution can be obtained by summing the areas of such strips over the entire distribution. The total area has been normalized by dividing it with the number of samples being used.

3.3 CHOICE OF SIGNAL

The effect of a disturbance in a dc transmission network or in the associated ac system, is reflected on the dc line in general as a variation in direct current and direct voltage. Any of these two quantities can be considered for the calculation of various time domain discriminants. However, as the occurrence of the short circuit faults is more frequent than the open circuit faults.Thus the direct current forms a convenient basis for the calculation of various time domain discriminants. Following most of the short circuit faults the direct voltage will collapse to zero. This may cause considerable computational problem in the evaluation of the discriminants. Following a disturbance, the direct current is sampled and used for the calculation of the discriminants. The direct current samples can be obtained for a reasonable period of time, say, for about two cycles or so.

3.4 CASE STUDY

For the calculation of time domain discriminants,a detailed dynamic digital simulation of two terminal hvdc system

Table 3.1 : List of disturbances

Case No.	Discription
1.	Single phase solid fault at inverter
2.	Single phase 80% dip at inverter
3.	Single phase 60% dip at inverter
4.	Single phase 40% dip at inverter
5.	Single phase 20% dip at inverter
6.	Two phase solid fault at inverter
7.	Three phase solid fault at inverter
8.	Remote three phase fault at inverter
9.	DC line fault in first Pi - section
10.	DC line fault in second Pi - section
11.	DC line fault in third Pi - section
12.	DC line fault in fourth Pi - section
13.	DC line fault in fifth Pi - section
14.	Single phase fault at rectifier
15.	Two phase fault at rectifier
16.	Three phase fault at rectifier

has been carried out to obtain the transient response of the direct current following various disturbances. The conventional controls for the converters have been considered here. The rectifier is equipped with constant current and minimum alpha control. The inverter is equipped with constant current and constant extinction angle control.

The various faults considered on the ac and dc sides are listed in Table 3.1. The direct current response for the various cases are given in Figures 3.1 to 3.16. The responses shown, are for a period of two ac cycles (40 ms) from the instant of initiation of fault. Utilizing the sampled values of the direct current, the time domain discriminants discussed in section 3.2, have been evaluated and presented in Table 3.2. It can be observed from Table 3.2 that the values of discriminants are quite close for some of the disturbances. For example, the Mean value discriminant for two phase solid fault at inverter is 1.375203 and that for single phase 80% dip at inverter it is 1.374784. Similarly the value of Variance for single phase solid fault at inverter is 0.082278 and that for single phase 80% dip it is 0.082507. Thus due to the closeness in the values of discriminants for different faults, it may be difficult to differentiate the faults based on the individual discriminants alone. However, a combination of discriminants can successfully be used for identifying the type of fault. For an example, the two phase solid fault and single phase 80% dip, which may not be discriminated using Mean value, can be discriminated at the second level of decision based on the Variance. For some of the faults more number of decision levels may be required. This may

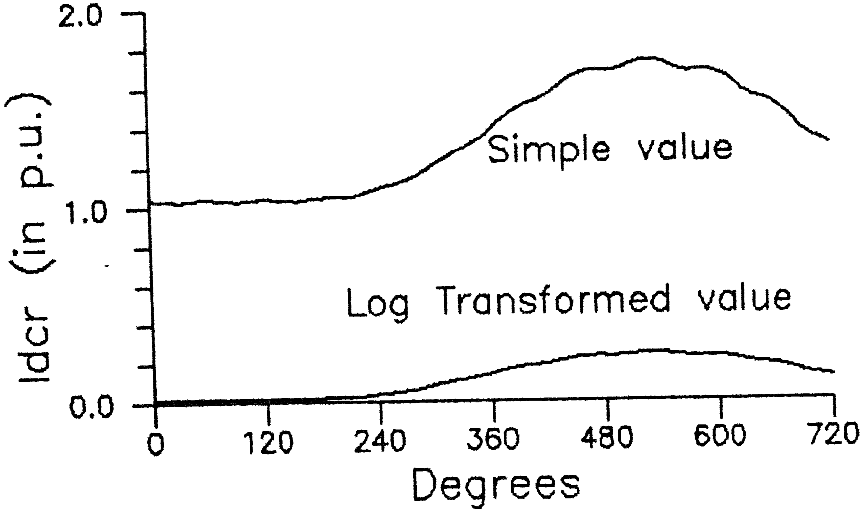


Fig. 3.3: Case 3

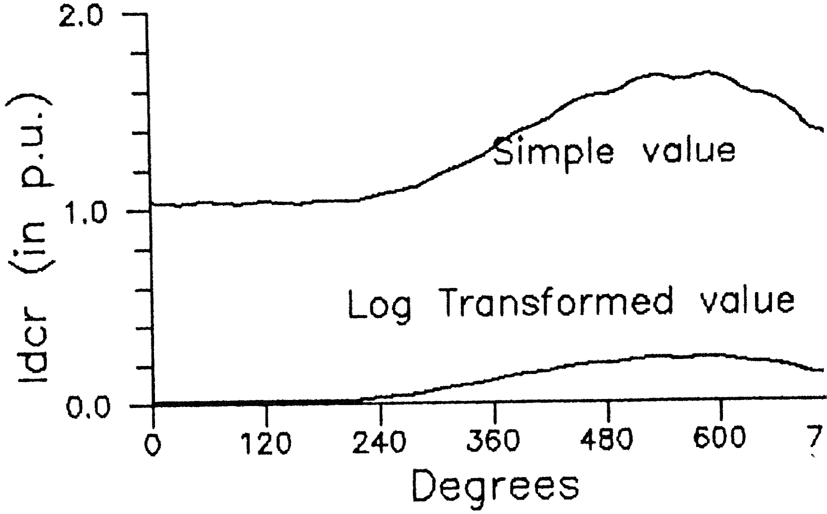


Fig. 3.4: Case 4

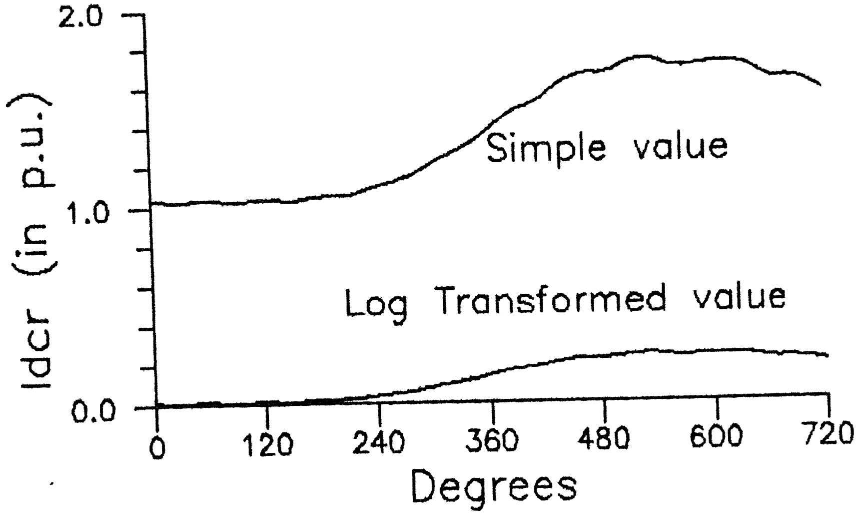


Fig. 3.1: Case 1

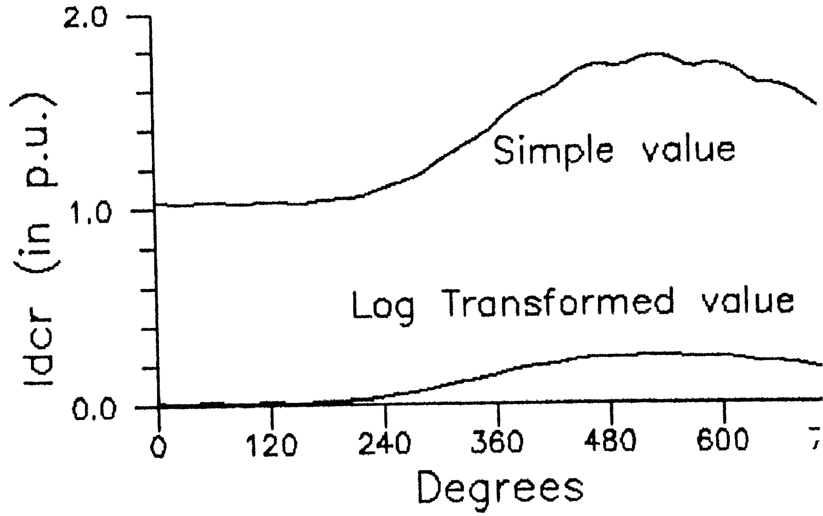


Fig. 3.2: Case 2

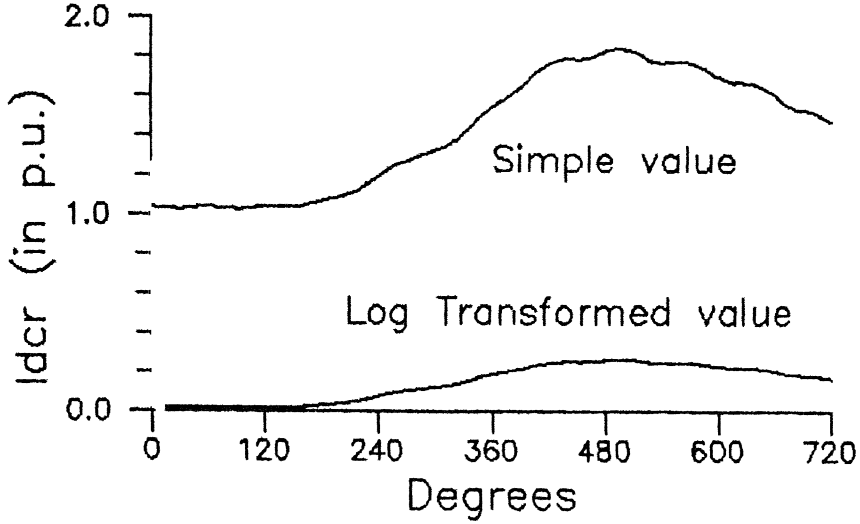


Fig. 3.7: Case 7

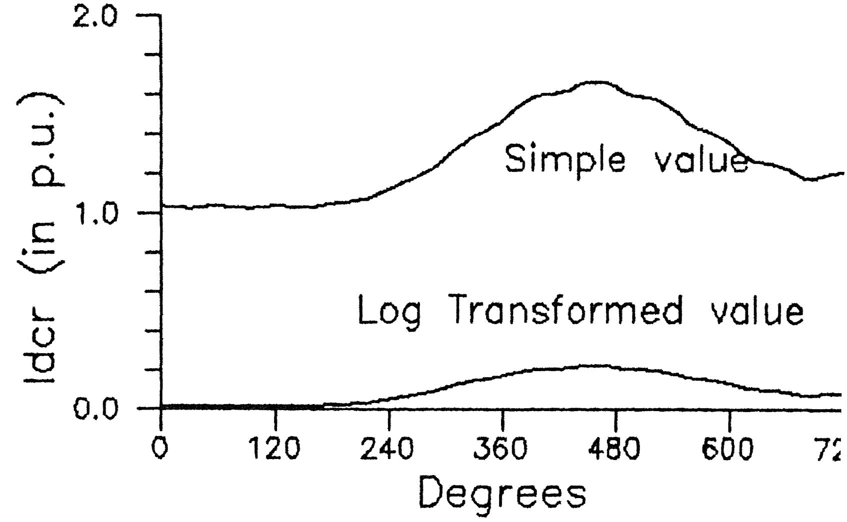


Fig. 3.8: Case 8

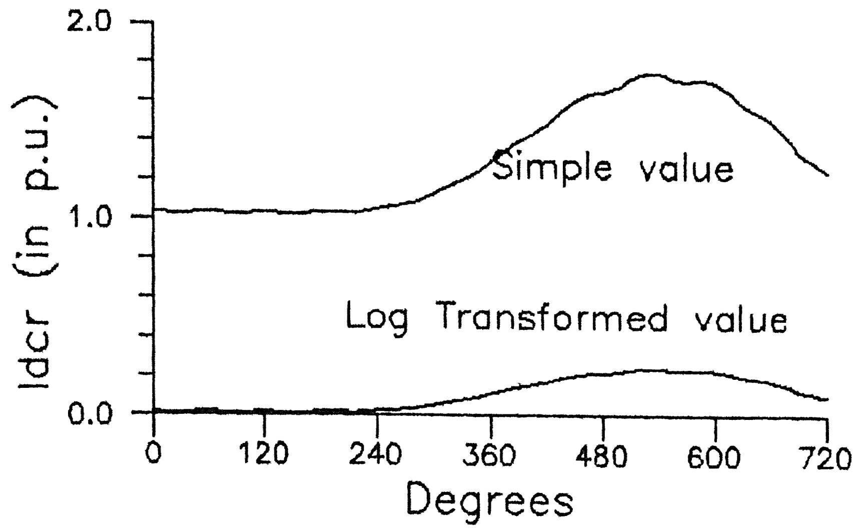


Fig. 3.5: Case 5

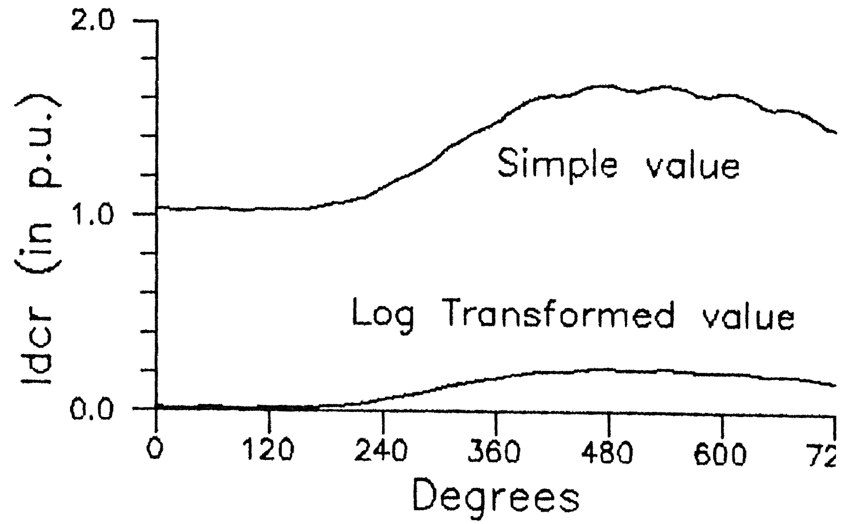


Fig. 3.6: Case 6

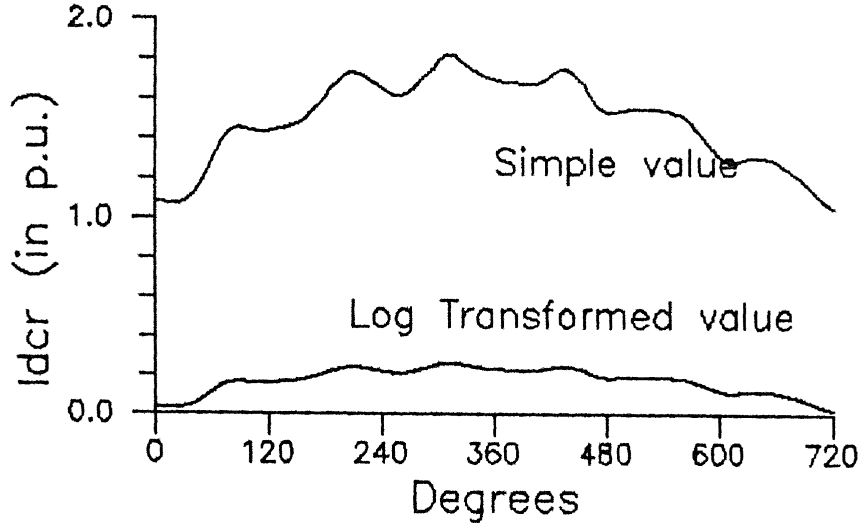


Fig. 3.11: Case 11

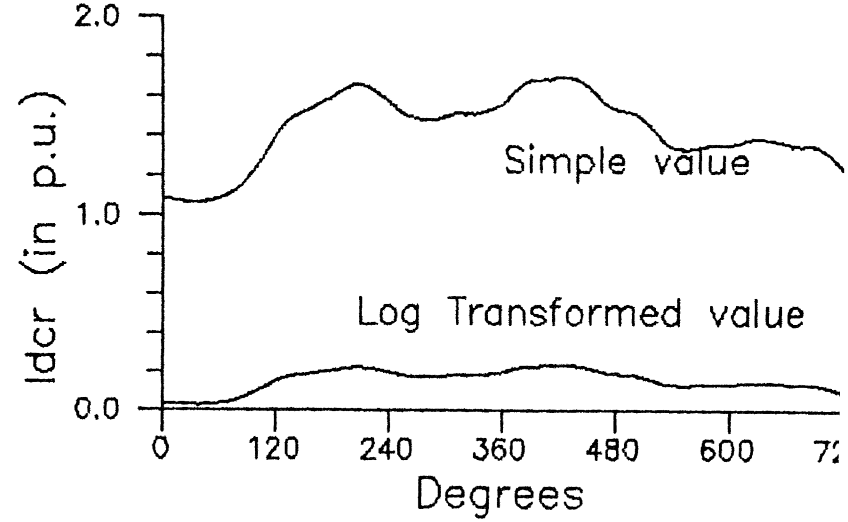


Fig. 3.12: Case 12

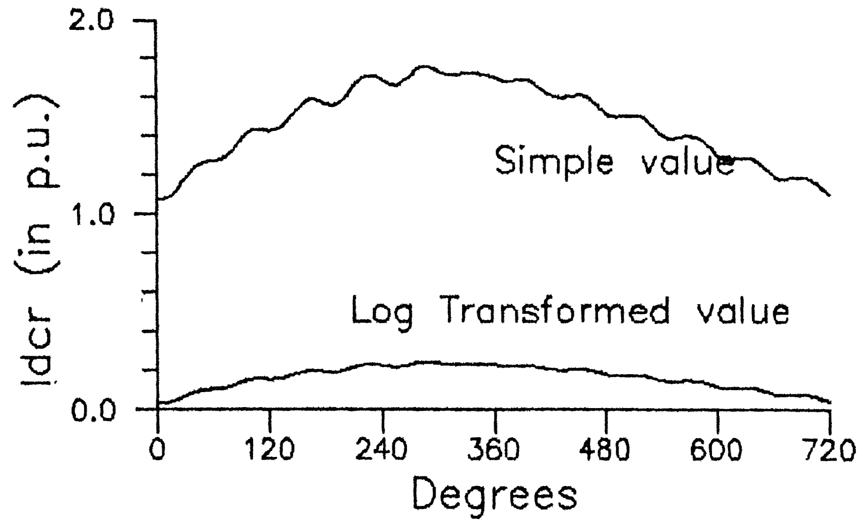


Fig. 3.9: Case 9

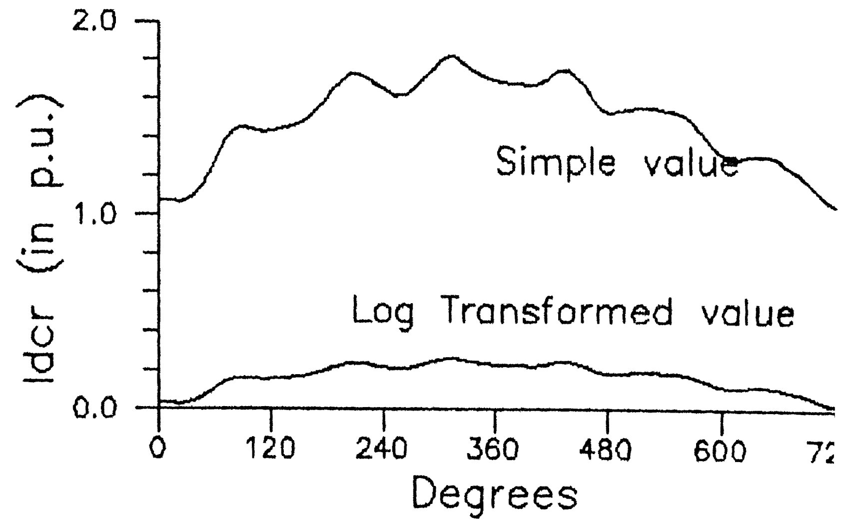


Fig. 3.10: Case 10

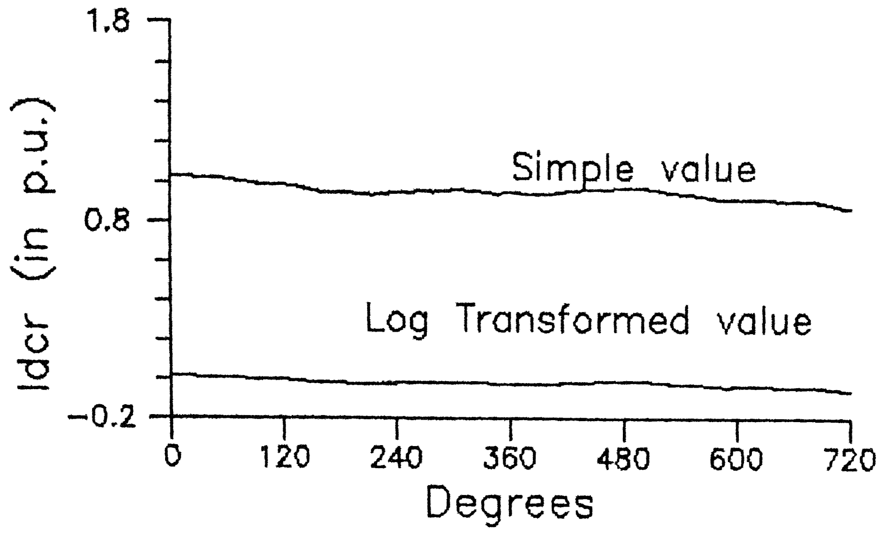


Fig. 3.15: Case 15

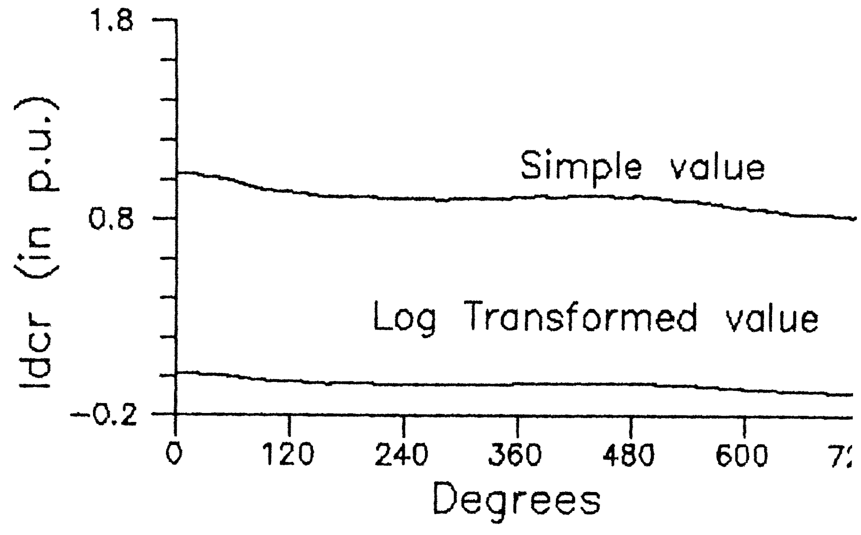


Fig. 3.16: Case 16

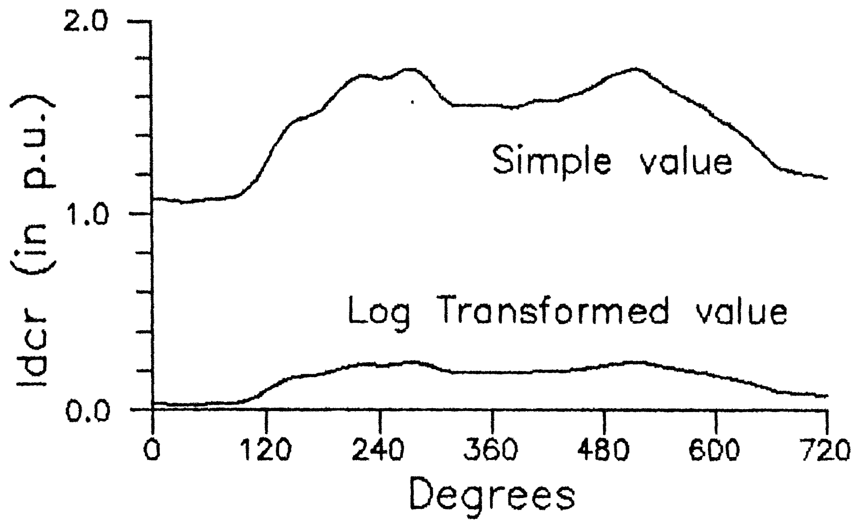


Fig. 3.13: Case 13

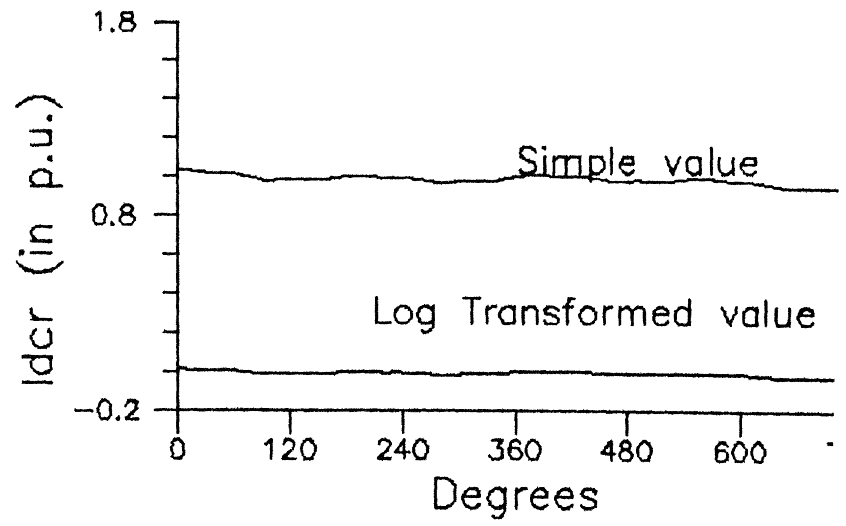


Fig. 3.14: Case 14

Table 3.2: Time Domain Discriminants

SL. NO.	DISTURBANCES	MEAN	VARIANCE	SKEWNESS	KURTOSIS	STANDARD DEVIATION	AREA (NORM.)
1.	SINGLE PHASE SOLID FAULT AT INVERTER	1.369852	0.082278	-0.010320	1.237443	0.286841	1.369502
2.	TWO PHASE SOLID FAULT AT INVERTER	1.375203	0.067196	-0.253710	1.327193	0.259221	1.374815
3.	THREE PHASE SOLID FAULT AT INVERTER	1.425337	0.091607	-0.122627	1.393657	0.302667	1.424979
4.	REMOTE THREE PHASE FAULT AT INVERTER	1.290020	0.049959	0.309296	1.638258	0.223516	1.289580
5.	REMOTE SINGLE PHASE FAULT AT INVERTER						
	(a) 80 % DIP	1.374784	0.082507	-0.028725	1.284004	0.287241	1.374408
	(b) 60 % DIP	1.340356	0.071806	0.106242	1.370598	0.267966	1.339941
	(c) 40 % DIP	1.308638	0.061382	0.144883	1.360931	0.247754	1.308230
	(d) 20 % DIP	1.318733	0.074589	0.296910	1.464522	0.273111	1.318305
6.	DC LINE FAULT						
	(a) FIRST π SECTION	1.481346	0.038737	-0.324112	1.846820	0.196818	1.480856
	(b) SECOND π SECTION	1.497383	0.044361	-0.526627	2.197448	0.210620	1.496882
	(c) THIRD π SECTION	1.487688	0.038972	-0.543847	2.424720	0.197413	1.487213

Table 3.2:(Contd.)

SL. NO.	DISTURBANCES	MEAN	VARIANCE	SKEWNESS	KURTOSIS	STANDARD DEVIATION	AREA (NORM.)
	(d) FOURTH π SECTION	1.436798	0.031491	-0.579738	2.568299	0.177456	1.436334
	(e) FIFTH π SECTION	1.477061	0.049362	-0.673334	2.067231	0.222175	1.476589
7.	SINGLE PHASE FAULT AT RECTIFIER	0.986831	0.000462	-0.273293	3.123695	0.021495	0.986331
8.	TWO PHASE FAULT AT RECTIFIER	0.947498	0.001298	-0.134391	3.319122	0.036028	0.946982
9.	THREE PHASE FAULT AT RECTIFIER	0.910796	0.002303	0.445382	3.693644	0.047896	0.910267

ultimately slow down the decision making process, and the advantage of using the time domain discriminants for identification may be lost.

From the above discussion it is evident that in order to discriminate the various faults successfully either a combination of various discriminants should be used or if the identification is to be based on single discriminant alone then a choice of an alternate signal for the evaluation of discriminants should be explored.

3.5 LOG TRANSFORMATION

For calculating the various time domain discriminant, the log transformed value of direct current can be considered as an alternate signal. This can be obtained by performing the log transformation on the direct current. This has the following features [13].

(a) The direct current can be normalised to 1.0 p.u. in the steady state and the logarithm of 1.0 is zero. Thus any definite value of log transformed direct current will indicate the disturbance in the system.

(b) The data which is segregated can be compressed and wild variations can be smoothed out with the use of log - transformation.

(c) The log transformation performed on the signal of interest improves the resolution in the values of discriminants.

3.6 CASE STUDY

The log transformed value of direct current signal

Table 3.3: Time Domain Discriminants (Log - Transformed Values)

SL. NO.	DISTURBANCES	MEAN	VARIANCE	SKEWNESS	KURTOSIS	STANDARD DEVIATION	AREA (NORM.)
1.	SINGLE PHASE SOLID FAULT AT INVERTER	0.126870	0.008624	-0.085301	1.239798	0.092887	0.126906
2.	TWO PHASE SOLID FAULT AT INVERTER	0.130203	0.007284	-0.328504	1.356649	0.085346	0.130228
3.	THREE PHASE SOLID FAULT AT INVERTER	0.143622	0.009161	-0.241916	1.409019	0.095712	0.143657
4.	REMOTE THREE PHASE FAULT AT INVERTER	0.104159	0.005557	0.171144	1.563069	0.074544	0.104168
5.	REMOTE SINGLE PHASE FAULT AT INVERTER						
	(a) 80 % DIP	0.128440	0.008633	-0.115204	1.274836	0.092916	0.128469
	(b) 60 % DIP	0.118428	0.007679	0.002307	1.333549	0.087629	0.118444
	(c) 40 % DIP	0.100993	0.006810	0.052679	1.316128	0.082522	0.109012
	(d) 20 % DIP	0.110952	0.007940	0.186481	1.382682	0.089106	0.110965
6.	DC LINE FAULT						
	(a) FIRST π SECTION	0.166643	0.003570	-0.484054	2.038748	0.059750	0.166632
	(b) SECOND π SECTION	0.170715	0.004166	-0.736104	2.500791	0.064548	0.170698
	(c) THIRD π SECTION	0.168409	0.003701	-0.785434	2.789191	0.060834	0.168402

Table 3.3: (Contd.)

SL. NO.	DISTURBANCES	MEAN	VARIANCE	SKEWNESS	KURTOSIS	STANDARD DEVIATION	AREA (NORM.)
	(d) FOURTH π SECTION	0.153849	0.003194	-0.821177	2.915750	0.056515	0.153847
	(e) FIFTH π SECTION	0.164016	0.004896	-0.816961	2.251916	0.069971	0.164011
7.	SINGLE PHASE FAULT AT RECTIFIER	-0.005861	0.000090	-0.340012	3.140230	0.009494	0.005877
8.	TWO PHASE FAULT AT RECTIFIER	-0.023738	0.000275	-0.262226	3.251362	0.016589	0.023761
9.	THREE PHASE FAULT AT RECTIFIER	-0.041175	0.000516	0.251527	3.516413	0.022709	0.041206

has been used to calculate the time domain discriminants described in section 3.2. It can be observed from the Table 3.3 that the sign of the Mean value indicates whether the fault is on rectifier side or on inverter side. The Mean value for two phase solid fault is 0.130203 and that for single phase 80% dip it is 0.128440. Thus the Mean value obtained from the log - transformed value of direct current can discriminate these cases. It has been shown in section 3.4 that these cases were difficult to discriminate using Mean value obtained from the direct current signal. Further, the value of Variance for single phase solid fault is 0.008624 and that for single phase 80% dip it is 0.008633. Due to the closeness in the values, the Variance can not discriminate these disturbances.

Thus the discriminants obtained from the log - transformed value of direct current also , can not identify all of the faults when the decision is based on individual discriminants alone.

3.7 CONCLUSIONS

The various time domain discriminants have been discussed and calculated. The signals used for calculation were the direct current and its log transformed value. It has been concluded that all of the faults can not be identified using individual discriminants alone. By using the discriminants obtained from both the signals simultaneously a good decision about the type of disturbance could be reached. However, a large number of comparisons may be required to identify a fault when the decision is based on individual discriminants alone. This may slow down the decision making process.

CHAPTER 4

PATTERN MATCHING FOR FAULT DIAGNOSIS

4.1 INTRODUCTION

The time domain discriminants have been calculated from the signal of interest and its log - transformed value in the last chapter. The problems associated with the identification of faults, when individual discriminants are used separately, have already been discussed in the previous chapter. To circumvent these problems various discriminants can be used in an organised manner through a pattern matching technique. The pattern matching techniques based on these discriminants are given in the literatures [5-6]. In this chapter a pattern matching technique has been discussed and used for the fault diagnosis.

4.2 PATTERN MATCHING TECHNIQUE

The pattern matching technique which has been used for the fault diagnosis is based on the concept of distance measure. This technique has been discussed below.

4.2.1 Distance Measure

The distance is the crucial concept in pattern matching. Closer a point to another point, more similar are the patterns represented by those points [6]. The patterns corresponding to various disturbances can be described by a set of time domain discriminants. These patterns form a domain. In this domain various disturbances are represented by points. The new pattern corresponding to an unknown disturbance, can also be represented as a point in the domain of patterns. The distances, between the point corresponding to new pattern and the points

corresponding to the patterns available, are obtained. The new pattern will be similar to the pattern for which the distance obtained is minimum.

The distance can be obtained using any distance function which satisfies the following constraints.

(a) $d(x,x) = 0$

(b) $d(x,y) > 0$

(c) $d(x,y) = d(y,x)$ and,

(d) $d(x,y) + d(y,z) \geq d(x,z)$

The conventional Euclidean distance function satisfies the above constraints. The Euclidean distance function can be given as

$$d_{1k} = \left[\sum_{i=1}^{n} (x_i - y_{ik})^2 \right]^{1/2}$$

where,

x_i = The value of i^{th} discriminant describing the new pattern

y_{ik} = The value of i^{th} discriminant describing the k^{th} pattern

n = Number of discriminants

d_{1k} = The distance between new pattern and the k^{th} pattern

In the literatures [5-6], normalized samples of the patterns are used for obtaining the distance. It has been shown in reference [13] that the values of the time domain discriminants do not change significantly for samples/cycle more than 32. The two cycles information, from the initiation of fault, have been used to calculate these discriminants and hence

... If the samples of signal

are used to describe a pattern then the total number of data to be stored will be 64.n, where, n is the total number of patterns. However, if the information contained in the samples of pattern is stored as a set of time domain discriminants then number of data to be stored will be considerably reduced. For an example , if three discriminants are used to describe a pattern the total number of data to be stored will be 3.n for n patterns. Hence, large number of memory space is required when the sampled value is used to describe the pattern. Further , this may slow down the decision making process. Thus instead of describing a pattern by its sampled value it can be described by the discriminants calculated from these samples.

4.3 THE SELECTION OF DISCRIMINANTS

The pattern corresponding to various disturbances are described by a set of time domain discriminants. The elements in the set of time domain discriminants are Mean, Variance, Skewness, Kurtosis, Standard Deviation, Normalized Area and their log - transformed values. It has been shown in chapter 3 that the combination of these discriminants should be used to discriminate all the faults. If all of these discriminants are used independently, a large number of comparisons may be required in making decision about the type of fault. However, these discriminants when used through a pattern matching technique can successfully discriminate all the faults and the comparisons required may be less. The computational time, in making the decision, depends upon the number of discriminants in a set and the number of decision levels required to reach the decision. The

number of the decision level depends upon how efficiently the discriminants have been selected. The number of discriminants in a set should be such that a right decision can be made with less number of decision levels. During the investigation it has been found that the minimum number of discriminants, which can successfully describe the pattern, are three.

4.4 DECISION MAKING PROCESS

To reduce the number of comparisons required to identify the type of disturbance, various Classes of disturbances have been defined. The Class may contain different Subclasses corresponding to various disturbances. It has been shown in chapter 3 that log - transformed value of direct current shows better trending. This property has been exploited in classifying the various disturbances. It has been found that the Mean, Variance and Standard Deviation obtained from the log - transformed value of direct current could be used to describe the various Classes of disturbances. The various Subclasses are described by simple values of Skewness, Variance and Standard Deviation. The various Classes and Subclasses are given in Table 4.1. This classification is based on the values of discriminants and has been developed through investigations.

At the most, the two decision levels are required to identify a fault as observed from Table 4.1. For an example, if in the first level of decision it has been decided that the new pattern belongs to Class 6, the second level of decision will give the Subclass to which it belongs. Thus in two decision levels the type of disturbance can be identified.

Table 4.1 : Classification of Disturbances

Class	Subclass	Description
1		Single phase fault at inverter
	a	- Solid fault
	b	- 80% dip
2		Two phase fault at inverter
3		Three phase fault at inverter
4		Remote single phase fault at inverter
	a	- 60% dip
	b	- 40% dip
	c	- 20% dip
5		Remote three phase fault at inverter
6		DC line fault
	a	- First Pi - section
	b	- Second Pi - section
	c	- Third Pi - section
	d	- Fourth Pi - section
	e	- Fifth Pi - section
7		Single phase fault at rectifier
8		Two phase fault at rectifier
9		Three phase fault at rectifier

4.5 RESULTS AND DISCUSSION

A software has been developed which employs the pattern matching technique for the identification of faults. The Flow Chart for this has been given in Figure 4.1. The software developed has been incorporated in the existing digital computer program used for the dynamic digital simulation of the hvdc transmission system. The knowledge about the system behaviour corresponding to the various disturbances has been stored in terms of time domain discriminants. The various Classes of disturbances have been described by log - transformed Mean, Variance and Standard Deviation. In a particular Class, various Subclasses are described by simple Skewness, Variance and Standard Deviation. The reduced pattern space is given in Table 4.2.

The dynamic digital simulation of the hvdc transmission system including the software developed for fault diagnosis has been carried out. The identification of the various disturbances listed in Table 3.1 has been validated. The various test simulations has been carried out to examine the influence of the fault duration, other control strategy and change in the ac system impedance on identification process.

4.5.1 Influence of Fault Duration

Since, two cycles information about the direct current variation has been used in the identification process,therefore,the fault diagnosis technique does not depend upon the duration of fault. The reduced pattern space given in Table 4.2, has been used as knowledge about the disturbances.

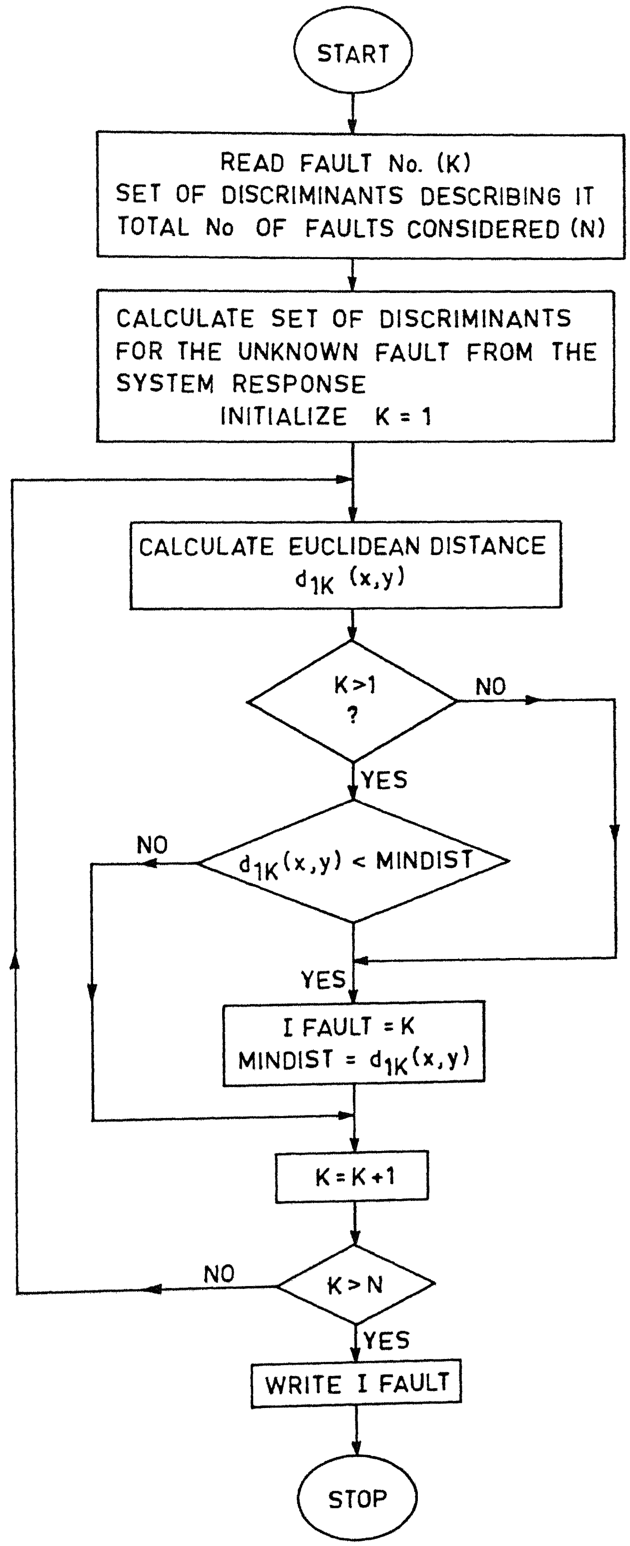


Fig. 4.1. Flow Chart of Fault Diagnosis Software.

Table 4.2: Reduced Pattern Space (with conventional control)

SL. NO.	DISTURBANCES	Simple Discriminants VARIANCE	SKEWNESS	STANDARD DEVIATION	Log Transformed Discriminant MEAN	VARIANCE	STANDARD DEVIATION
1.	SINGLE PHASE FAULT AT INVERTER				0.126870	0.008624	0.092867
	(a)SOLID FAULT	0.082278	-0.010320	0.286841			
	(b)80 % DIP	0.082507	-0.028725	0.287241			
2.	TWO PHASE SOLID FAULT AT INVERTER				0.130203	0.007284	0.085346
3.	THREE PHASE SOLID FAULT AT INVERTER				0.143622	0.009161	0.095712
4.	REMOTE THREE PHASE FAULT AT INVERTER				0.104159	0.005557	0.074544
5.	REMOTE SINGLE PHASE FAULT AT INVERTER				0.110952	0.007940	0.089106
	(a) 60 % DIP	0.071806	0.106242	0.267966			
	(c) 40 % DIP	0.061382	0.144883	0.247754			
	(d) 20 % DIP	0.074589	0.296910	0.273111			
6.	DC LINE FAULT				0.164016	0.004896	0.069971
	(a) FIRST π SECTION	0.038737	-0.324112	0.196818			
	(b) SECOND π SECTION	0.044361	-0.526627	0.210620			
	(c) THIRD π SECTION	0.038972	-0.543847	0.197413			

Table 4.2:(Continued)

SL. NO.	DISTURBANCES	Simple Discriminants: VARIANCE	Simple Discriminants: SKEWNESS	Simple Discriminants: STANDARD DEVIATION	Log Transformed Discriminants: MEAN	Log Transformed Discriminants: VARIANCE	Log Transformed Discriminants: STANDARD DEVIATION
	(d) FOURTH π SECTION	0.031491	-0.579738	0.177456			
	(e) FIFTH π SECTION	0.049362	-0.673334	0.222175			
7.	SINGLE PHASE FAULT AT RECTIFIER				-0.005861	0.000090	0.009494
8.	TWO PHASE FAULT AT RECTIFIER				-0.023738	0.000275	0.016589
9.	THREE PHASE FAULT AT RECTIFIER				-0.041175	0.000516	0.022709

This has been obtained from the system response when the system is subjected to a disturbance of 3 cycle duration. The identification of the faults has been found to be independent of the duration of fault when the fault duration is increased to 4 or 5 cycles.

4.5.2 Influence of Control

The proposed identification technique can be used to identify the disturbances when the system operating condition is changed. To illustrate this point, a different system operating condition has been chosen. The hvdc transmission systems are generally equipped with constant current and constant extinction angle controls. These are the conventional control strategies. The constant reactive current control, which is an unconventional control, has been considered for the inverter terminal. From the system response , with constant reactive current control for the inverter, the various discriminants have been calculated. The reduced pattern space has been given in Table 4.3. This has been used as a knowledge about the various disturbances.

If the hvdc transmission system is equipped with conventional as well as unconventional control,the control strategy will always be known apriori. However, the change in the control strategies may be detected as a fault. In either case the corresponding pattern space (data set) can be selected. The identification technique remains the same, only the knowledge has to be updated.

Table 4.3: Reduced Pattern Space (with unconventional control)

SL. NO.	DISTURBANCES	Simple Discriminants: VARIANCE	Simple Discriminants: SKEWNESS	Simple Discriminants: STANDARD DEVIATION	Log Transformed Discrimina: MEAN	Log Transformed Discrimina: VARIANCE	Log Transformed Discrimina: STANDARD DEVIATIOI
1.	SINGLE PHASE FAULT AT INVERTER				0.126640	0.008524	0.092326
	(a)SOLID FAULT	0.081002	-0.023550	0.284609			
	(b)80 % DIP	0.080145	-0.033931	0.283099			
2.	TWO PHASE SOLID FAULT AT INVERTER				0.129634	0.007209	0.084907
3.	THREE PHASE SOLID FAULT AT INVERTER				0.143898	0.009155	0.095684
4.	REMOTE THREE PHASE FAULT AT INVERTER				0.101059	0.005529	0.074356
5.	REMOTE SINGLE PHASE FAULT AT INVERTER				0.110546	0.007881	0.088773
	(a) 60 % DIP	0.071685	0.105488	0.267740			
	(c) 40 % DIP	0.080599	0.217826	0.283899			
	(d) 20 % DIP	0.073929	0.301718	0.271899			
6.	DC LINE FAULT				0.176687	0.004026	0.063450
	(a) FIRST π SECTION	0.045300	-0.363179	0.212838			
	(b) SECOND π SECTION	0.051686	-0.552901	0.227346			
	(c) THIRD π SECTION	0.043876	-0.575648	0.209467			

Table 4.3:(Continued)

SL. NO.	DISTURBANCES	Simple Discriminants: VARIANCE	Simple Discriminants: SKEWNESS	Simple Discriminants: STANDARD DEVIATION	Log Transformed Discriminants: MEAN	Log Transformed Discriminants: VARIANCE	Log Transformed Discriminants: STANDARD DEVIATION
	(d) FOURTH π SECTION	0.041695	-0.717278	0.204198			
	(e) FIFTH π SECTION	0.060147	-0.705201	0.245248			
7.	SINGLE PHASE FAULT AT RECTIFIER				-0.003827	0.000060	0.007757
8.	TWO PHASE FAULT AT RECTIFIER				-0.020113	0.000169	0.012986
9.	THREE PHASE FAULT AT RECTIFIER				-0.037612	0.000382	0.019540

4.5.3 Influence of the Change in AC System Impedance

The dynamic digital simulation of hvdc transmission system including the software developed for fault diagnosis, has been carried out with the change in ac system impedance. It has been found that ±10% change in ac system impedance does not affect the system response greatly and various faults can be identified faithfully without change in the knowledge. If ac system impedance is changed such that it affects the system response to the various disturbances then also the various faults can be identified by selecting the appropriate pattern space. The fault diagnosis technique remains same.

4.6 CONCLUSIONS

A pattern matching technique has been discussed and used for the identification of various faults. The decision rule is based on the minimum distance concept. The dynamic digital simulation of the hvdc system including the software developed for fault diagnosis has been carried out. The following conclusions have been made.

(1) The discriminants obtained from the log - transformed value of signal can be used to define the various Classes of patterns.

(2) Three discriminants are required to describe a pattern.

(3) The right decision about the type of fault can not be made until the knowledge, about the system behaviour stored as a set of discriminants, is correct. With the change in system operating conditions such as change in ac system impedance or

change in control strategy, the system response gets modified and corresponding pattern space should be selected. In any case the fault diagnosis technique remains same.

CHAPTER 5

CONCLUSIONS

This thesis has mainly been devoted to the software development for fault diagnosis of the hvdc system based on pattern matching technique.

The dynamic digital simulation of the hvdc system has been carried out to obtain the system response to various disturbances. The disturbances considered are the ac voltage dips and dc line faults occurring at different locations on the dc line. The system response thus obtained is used to calculate the time domain discriminants. The direct current pattern during the fault and its log - transformed value have been used to calculate these discriminants. The direct current response to various disturbances has been described by a set of discriminants. A pattern matching technique based on distance measure has been used to identify the various faults.

The hvdc transmission system is normally equipped with constant current and constant extinction angle control. These are the conventional controls for the hvdc transmission system. An unconventional control (Constant Reactive Current Control) for inverter terminal has also been considered. This has been done to examine the influence of the system operating condition on the identification process.

The salient findings of the present investigation are given below:

(1) The individual time domain discriminants can not differentiate all the faults. A good decision about the type of fault can be made using more number of discriminants

individually. However, a large number of comparisons are required to identify the type of disturbance. This may slow down the decision making process.

(2) The patterns of the direct current and its log - transformed value corresponding to various disturbances can be described by a set of time domain discriminants, instead of its sampled value taken at appropriate interval. This will reduce the memory requirement for storing the patterns.

(3) A pattern matching technique based on the distance measure can successfully identify the various disturbances.

(4) The minimum number of discriminants which can describe a pattern successfully are three.

(5) The fault diagnosis technique based on pattern matching is independent of the duration of faults.

(6) This technique can successfully identify the location of dc line fault.

(7) Under the different system operating conditions, such as change in short circuit ratio of ac system and control strategy, for which the system behaviour following a disturbance gets modified a different set of knowledge corresponding to that operating condition is required.

The major emphasis in the present study has been on the development of fault diagnosis technique using pattern matching. The various disturbances considered are the ac voltage dips on the rectifier as well as the inverter side and dc line faults. As an extension of this work in future, it would be worth studying the following aspects:

(1) The identification of converter faults using pattern matching.

(2) The decision rule can be made adaptive.

(3) Development of an Expert System for the hvdc transmission system.

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APPENDIX A

SYSTEM DATA (adapted from reference [11])

DC base voltage = 100 kV

DC base current = 1 kA

DC base impedance = 100 Ohms

Rated Power of DC Link = 240 MW for 12 pulse system

= 120 MW for 6 pulse system

AC system frequency = 50 Hz

Bridge Transformer:

Resistance $R_{c1} = R_{c2} = 0.5$ Ohms

Commutating Reactance $X_{c1} = X_{c2} = 6.283$ Ohms

Smoothing Reactor:

Resistance $R_{d1} = R_{d2} = 0.1$ Ohms

Reactance $X_{d1} = X_{d2} = 314.159$ Ohms

Transmission Line:

Total resistance = 8.64 Ohms

Total inductance = 0.50148 H

Total capacitance = 54.1645 μF

Any number of PI sections upto a maximum of 10 may be spe

Digital Controller

a) Constant Current Controller

$K_1 = 0.4$ radians/per unit current

$K_2 = 0.4$ radians^2/per unit current

b) Constant Extinction Angle Controller

$K_3 = 1.0$

$K_4 = 0.25$

RMS AC Voltages (L-N)

$E_1 = 42.78$ kV, $E_2 = 38.51$ kV

Valve turn off time $= 3°$

Operating conditions:

a) 12 pulse:

$I_{d1} = I_{d2} = 1000$ Amps

$\alpha_{min} = 5°$, $\gamma_c = 10°$

$\alpha_1 = 26.22°$, $\alpha_2 = 148.39°$

b) 6 pulse:

$I_{d1} = I_{d2} = 1000$ Amps

$\alpha_{min} = 5°$, $\gamma_c = 10°$

$\alpha_1 = 12.88°$, $\alpha_2 = 148.38°$

DC Filter parameters:

$R = 0.096$ p.u.

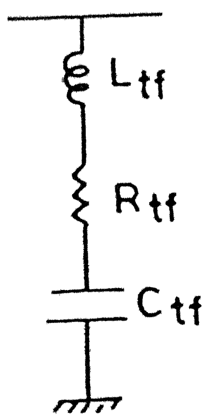
$L_1 = 0.20267$ p.u.

$L_2 = 0.5947411$ p.u.

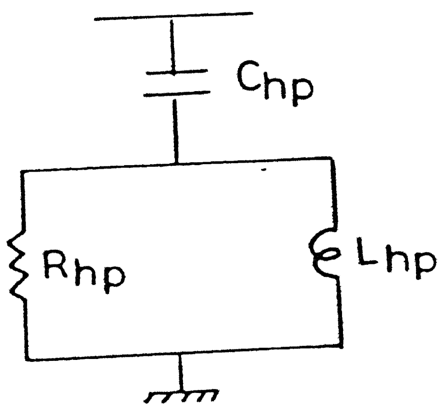
$C_1 = 0.047183$ p.u.

$C_2 = 0.136659$ p.u.

AC Filter Configuration:



Series Tuned Filter



High Pass Filter

AC Filter Parameters

Harmonic No.	Resistance Ohms	Inductance mH	Capacit μF
5	1.11418	36.32860	11.13
7	0.801103	18.16430	11.13
11	0.504805	7.26573	11.51
13	0.4225	5.20478	11.53
HP	16.1428	3.00410	11.57

VDCOL Parameters:

6 Pulse Operation

a) At Rectifier

T_{DN} = 0.00008 sec; T_{UP} = 0.03 sec

Corner points:

Voltage (p.u.):	0.6	0.2	0.0
Current (p.u.):	1.0	0.4	0.4

b) At Inverter

T_{DN} = 0.00008 sec; T_{UP} = 0.04 sec

Corner points:

Voltage (p.u.):	0.6	0.2	0.0
Current (p.u.):	0.9	0.3	0.3

12 Pulse Operation

a) At Rectifier

T_{DN} = 0.00008 sec; T_{UP} = 0.03 sec

Corner points:

Voltage (p.u.):	1.2	0.4	0:0
Current (p.u.):	1.0	0.4	0.4

b) At Inverter

$T_{DN} = 0.00008$ sec; $T_{UP} = 0.04$ sec

Corner points:

Voltage (p.u.):	1.2	0.4	0.0
Current (p.u.):	0.9	0.3	0.3

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